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## Dilation of the giant vortex state in a mesoscopic superconducting loop

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**Abstract.** We have experimentally investigated the magnetisation of a mesoscopic aluminum loop at temperatures well below the superconducting transition temperature  $T_c$ . The flux quantisation of the superconducting loop was investigated by a  $\mu$ -Hall magnetometer in magnetic intensities between  $\pm 100$  Gauss. The magnetic intensity periodicity observed in the magnetisation measurements corresponds to integer values of the superconducting flux quantum  $\Phi_0 = h/2e$ . A closer inspection of the periodicity however reveal a systematic variation of the magnetic intensity periodicity. These variations we interpret as a consequence of a giant vortex state nucleating on either the inner or the outer side of the loop.

The measurement described in this paper were performed on a micron sized superconducting aluminium loop placed on top a  $\mu$ -Hall magnetometer. The  $\mu$ -Hall magnetometer was etched out of a GaAs/Ga<sub>0.7</sub>Al<sub>0.3</sub>As heterostructure. The mobility and electron density of the two-dimensional electron gas was  $\mu = 42 \text{ T}^{-1}$  and  $n = 1.9 \times 10^{15} \text{ m}^{-2}$ . A symmetrical  $4 \mu\text{m} \times 4 \mu\text{m}$  Hall geometry was defined by standard e-beam lithography on top of the heterostructure. In a later processing step a lift-off mask was defined on top of the  $\mu$ -Hall probe by e-beam lithography. After deposition of a  $t = 90 \text{ nm}$  thick layer of aluminium and lift-off the sample looked as presented in Fig. 1.

The mean radius of the aluminium loop was  $R = 2.16 \mu\text{m}$  and the average wire width  $w$  was  $316 \pm 40 \text{ nm}$ .

By using the expression

$$n\Phi_0 = n\frac{h}{2e} = \Delta(\mu_0 H)\pi R^2, \quad (1)$$

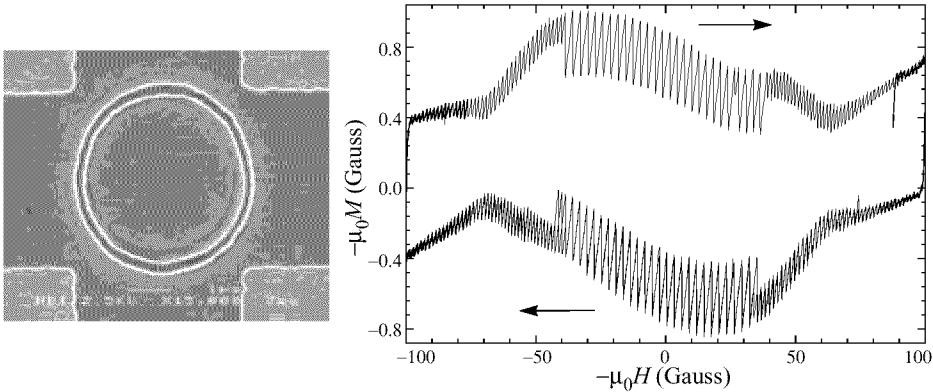
where  $A = \pi R^2$  is the area of the loop given by its mean radius  $R$ , it is found that a single flux jumps ( $n = 1$ ) corresponds to a magnetic intensity periodicity given by  $\Delta(\mu_0 H) = 1.412 \text{ Gauss}$ .

The samples was immersed in a <sup>3</sup>He cryostat equipped with a superconducting solenoid driven by a DC current supply. The relation between the Hall voltage  $V_H$  and the magnetic intensity  $H$  perpendicular to the  $\mu$ -Hall magnetometer is given by the classical Hall effect

$$V_H = -\frac{I}{ne}\mu_0(H + \alpha M), \quad (2)$$

were  $I$  is the DC current through the  $\mu$ -Hall magnetometer and  $\alpha$  is a dimensionless number of the order of unity, which corresponds to the ratio between the sensitive area of the  $\mu$ -Hall probe and the area of the object which is the source to the magnetisation  $M$ . In our case we find that  $\alpha$  typically was in the range between  $0.3 \dots 0.4$ .

By using standard AC lock-in techniques where the driving current  $I$  was modulated the Hall voltage  $V_H$  was measured as a function of magnetic intensity  $\mu_0 H$ .



**Fig. 1.** Left: Scanning electron microscope image of a  $\mu$ -Hall probe and aluminium loop. Right: Measured magnetisation  $\mu_0 M$  detected by the  $\mu$ -Hall probe as a function of magnetic intensity  $\mu_0 H$ . The curve displays distinct jumps corresponding to the abrupt changes in magnetisation of the superconducting loop when the system changes state. The measurements were performed at  $T = 0.36$  K.

In Fig. 1 is displayed the measured local magnetisation  $\mu_0 M$  detected by the  $\mu$ -Hall probe as a function of magnetic intensity  $\mu_0 H$ . The curve displays a series of distinct jumps corresponding to the abrupt changes in magnetisation of the superconducting loop. The difference in magnetic intensity between two successive flux jumps is approximately given by  $\Delta(\mu_0 H) = 1.4$  Gauss or  $\Delta(\mu_0 H) = 2.8$  Gauss which corresponds to either single or double flux jumps ( $n = 1$  or  $n = 2$ ).

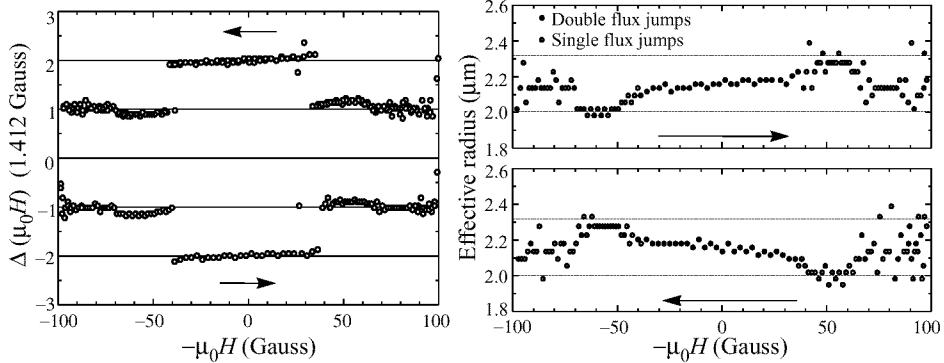
Large flux jumps ( $n > 1$ ) or flux avalanches, occur whenever the system is trapped in a metastable state. It was generally observed that these flux avalanches become more pronounced with decreasing temperature, at low magnetic intensities and for wide loops.

The energy barrier causing the metastability of the eigenstates of the loop, are due to either the Beam-Livingston surface barrier or the volume barrier, or even an interplay of both [1, 3, 4].

In Fig. 2 the magnetic intensity difference between successive jumps  $\Delta(\mu_0 H)$  in units of the 1.412 Gauss (corresponding to a single superconducting flux quantum), has been plotted as a function of magnetic intensity. It is seen that the magnetic intensity difference between the observed jumps is, to a high accuracy, given as integer values of 1.412 Gauss. At absolute magnetic intensities lower than 40 Gauss double flux jumps dominates, whereas at higher absolute magnetic intensities only single flux jumps are observed. The curve presents both an up sweep and a down sweep - indicated by the arrows.

For the graphs presented in Fig. 2 it is seen that a small systematic variation of the value of the flux jumps occur when the magnetic intensity is changed. This variation appear in the sense, that as the magnetic intensity is increased (decreased) the size of the flux jumps decreases (increases). Thus these deviations are depended, on not only the size of the magnetic intensity but also, on which direction the magnetic intensity was swept during measurements.

In the right part of Fig. 2 we use Eq. (1) to calculated the effective radius  $R$  of the superconducting loop and plot this radius as a function of magnetic intensity. The horizontal lines represents the mean inner  $R_i$  and outer radius  $R_o$  determined from the SEM picture. It is seen that as the magnetic intensity is changed from negative to positive values, the effective radius, as defined from the flux quantization condition of the loop, changes from



**Fig. 2.** Right: Effective radius  $R$  calculated by using Eq. (1). The filled (open) dots corresponds to single flux jumps  $n = 1$  (double flux jumps  $n = 2$ ). Left: The magnetic intensity difference  $\Delta(\mu_0 H)$  between two successive jumps in magnetisation. Given in units of 1.412 Gauss corresponding to a single flux quantum  $\Phi_0 = h/2e$ . The positive (negative) flux values corresponds to the case where  $\mu_0 H$  was decreased (increased) during the measurements. Arrows indicate sweep direction.

inner to outer radius and vice versa.

In a superconducting loop at low magnetic intensities, it is expected that the appropriate effective radius is given by the geometrical mean between outer and inner radius  $R = \sqrt{R_i R_o}$  [5]. This is in good agreement with the observed behavior around zero magnetic intensity.

However in the regime of high magnetic intensities the concept of surface superconductivity becomes important and a giant vortex state will occur. In this regime two degenerate current carrying situations are possible — the giant vortex state can either circulate the loop clockwise or anti-clockwise. In the case of a positive magnetic intensity, and a clockwise (anti-clockwise) circulating current the giant vortex state will nucleate at the outer (inner) edge of the loop. On the other hand if the magnetic intensity is negative the giant vortex state will nucleate at the inner (outer) radius of the loop [6].

The width of the giant vortex state is approximately given by the magnetic length  $l_H = \sqrt{\hbar/eH}$  [2]. Hence any variation of the effective radius should take place over a magnetic field range given by the condition that the width of the loop width of the loop and the magnetic length is comparable;  $w = l_H$ . Such an estimate gives a characteristic magnetic intensity of 34 Gauss in good agreement with the presented data in Fig. 2.

Since the orientation of the current in the loop is determined by the sweep direction (Lenz' law), a decreasing (increasing) magnetic intensity will give rise to an anti-clockwise (clockwise) circulation. Hence as the magnetic intensity is swept from e.g. a high positive value to a high negative value the effective radius of the loop will change from inner to outer radius and vice versa.

The important dimensionless parameter for comparison the presented results with the theoretical results in [7, 8, 9]; are given by the ratio  $x = R_i/R_o$  between outer and inner radius. In our case corresponding to  $x = 0.86$ .

Both theoretical groups find that at large  $x$  values (corresponding to a loop consisting of a one-dimensional wire) no or little variation of the effective radius should be observed. Whereas at small  $x$  values (corresponding to a disc) a fast decrease of the effective radius occur as the magnetic intensity increases. In the intermediate regime  $x = 0.5$ , a rather smooth transition between average and outer radius should take place when the magnetic

intensity increases.

In the presented measurement  $x = 0.75$ , we indeed observe that the effective radius vary smoothly between inner and outer radius. This behavior looks similar to the one predicted for loops with  $x = 0.5$ , however not similar to the one predicted expected for  $x = 0.75$ . However we do not find this discrepancy sever due to the following reasons: The calculations by Bruyndoncx et al. [9] were done using a linearized first Ginzburg–Landau equation, hence these results are only valid close to the phase transition, viz.  $R_o/\xi_o < 1$ . In the work by Peeters et al. [7, 8] the full set of non-linear Ginzburg–Landau equations were solved self-consistently, but under the assumption that  $R_o/\xi_o = 4$  and 2. Neither of these conditions were fulfilled in our experiments, were we estimate  $R_o/\xi_o \approx 20$ , it is furthermore seen by comparing the results of Peeters et al. that calculations with larger values of  $R_o/\xi_0$  properly would give rise to a better agreement.

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